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REPORT

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Water circulation in a fringing reef located in a monsoon area: Kabira Reef, Ishigaki Island, Southwest Japan

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Abstract Kabira Reef is a well-developed fringing reef situated in a monsoon area where the dominant wind direction changes seasonally: south in summer and north in winter. Circulation in this reef shows a marked wind influence. The circulation pattern under calm wind conditions is characterized by an inflow of ocean waters into the moat over the reef crest and an outflow through a prominent channel. Current vectors change according to wind conditions, and this pattern is weakened and strengthened under southern and northern wind conditions, respectively. We establish a simple model to explain these circulation patterns with two factors: wind and a fundamental circulation pattern under calm conditions. We estimate the ratios of the component of wind to that of the fundamental circulation. The ratios reach 3 and 10 in absolute values under southern and northern wind conditions, respectively. These results can be applied to water circulation throughout the year, with the southern wind-driven circulation dominant in the summer, and the northern wind-driven circulation dominant in the winter. While trade wind conditions often result in a constant circulation pattern, monsoonal wind conditions make the circulation pattern vary according to the seasons.

Key words Water circulation · Fringing reef
Monsoonal wind · Southwest Japan

Introduction

Water circulation is a major factor in determining the community structure and the exchange or the dispersal of materials in coral reefs. Lagoon circulation is mainly driven by tide, wind, and by wave-overtopping on the reef crest (Andrews and Pickard 1990).

The importance of wind on circulation in coral reefs has been shown in a deep atoll lagoon (Atkinson et al. 1981) and in platform reefs (Frith 1981; Frith and Mason 1986; Pickard 1986). For fringing reefs, wave-over-topping on the reef crest and the induced inflow is considered to be the main driving force of circulation in Caribbean reefs (Roberts et al. 1975; Roberts et al. 1992), while tide is thought to be the main driving force in fringing reefs in the Great Barrier Reef because of the large tidal ranges (Parnell 1988). Recent numerical modeling studies have considered the transfer of momentum caused by wave-overtopping (Prager 1991; Wolanski et al. 1994).

In comparison with deep atoll lagoons and platform reefs (Atkinson et al. 1981; Frith and Mason 1986), the effect of wind on circulation in fringing reefs has been discussed somewhat less than tides or wave-overtopping, although wave-overtopping depends on the ocean swell caused by winds. Also there has been little consideration of the effect of wind direction on circulation. The reason why wind is given little consideration is that most of the studies of water circulation on coral reefs have been in trade wind areas where wind conditions and induced ocean swells are generally constant. The effect of wind may be more important in coral reefs in the Ryukyu Islands which are located in a monsoon area characterized by opposite wind directions in summer and winter.

There have been few studies on fringing reefs in the Ryukyu Islands. Tanimoto and Uda (1990) observed the water circulation on Nakadomari Reef, Okinawa Island. They concluded that circulation was caused by wave-overtopping on the reef crest and the effect of wind was small. Nakamori et al. (1992) discussed the water circulation on Shiraho Reef, Ishigaki Island, based on observations of the current and study of the arrangements of coral patches. They concluded that the

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offshore waters enter the reef across the reef crest and return to the outer ocean directly through a channel. However, both studies give little consideration to wind direction. In regions with variable conditions, it is important to carry out observations under different wind conditions in order to generalize the circulation pattern in these coral reefs.

Pickard (1986) showed that the circulation on the reef flat is significantly influenced by wind direction, and estimated the ratio of wave-overtopping component to wind-driven component. He concluded that wind contributes 60% of the total; his study was conducted only on the shallow reef flat. However, in discussing the circulation or dispersal of materials around coral reefs, it is necessary to estimate the contribution of wind to the circulation in the lagoon or moat (shallow backreef lagoon).

Our study reports the circulation in Kabira Reef, a well-developed fringing reef located in a monsoon area. We examine circulation patterns under no wind, southern wind, and northern wind conditions. Then, according to these results, we present a simple model to explain the circulation in the lagoon and estimate the contribution of the wind to this circulation.

Methods

Study site

Kabira Reef is located on the western coast of Ishigaki Island, southwest Japan. Ishigaki Island is situated in a monsoon area, where the dominant wind direction is from the south in summer and from the north in winter. Over the entire year, northern winds are dominant (Fig. 1).

Figure 2a,b shows an aerial photograph and a geomorphological map of Kabira Reef, illustrating a well-developed fringing reef with a distinct topographical zonation from land to ocean: moat, reef pavement, reef crest, and reef edge. Kabira Reef stretches about 3 km in length along the shore, and it is about 800 m from the shoreline to the reef crest. The southeast side of Kabira Reef is bounded by the narrow and deep Kabira Channel. The depth is around 2 m in the moat, 0.9 m near the channel, 0.4–1.0 m on the area where reef rocks are exposed, and 0.6–1.0 m at the pavement and crest (Yamano, 1996). Areas less than 1 m deep are exposed during low spring tides.

Research methods

We set three transects labeled W, M, and E, from the beach to the reef crest, perpendicular to the shoreline (Fig. 2). The transects were located in the east side of Kabira Reef. We also set observation points on these transects. Each point is referred to its transect name and the distance (m) from the shoreline. For example, M700 is located 700 m from the shore along the M-line. W800 and M700 are located on the reef crest. M350, M100, and E350 are located in the moat.

Current directions and velocities were measured using five electromagnetic current meters (ACM-8M, Alec Electronics). They were set from noon on 11 March 1994 to 9:00 on 15 March at E350, M100, M350, M700, and from noon on 12 March to 9:00 on 15 March at W800. The sensors were set 50 cm above the bottom. Data on wind directions and velocities were collected by the Japan Sea-Farming Association, Yaeyama Station located on the same side of the island as Kabira Reef. We calculated the tide levels at Kabira Reef based on the tide table for Ishigaki Port published by the Meteorological Agency of Japan

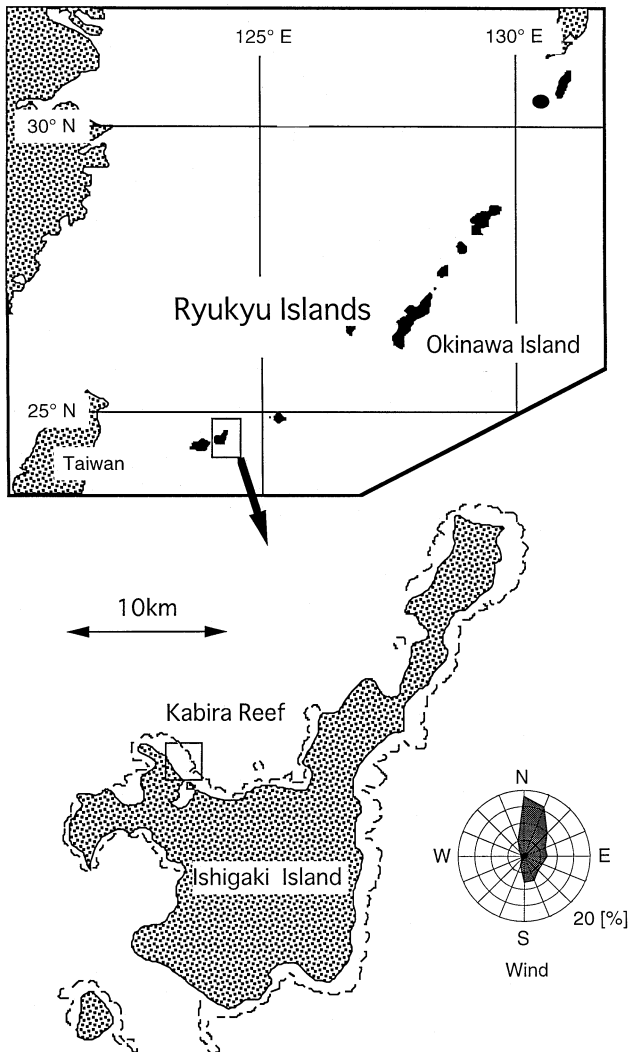
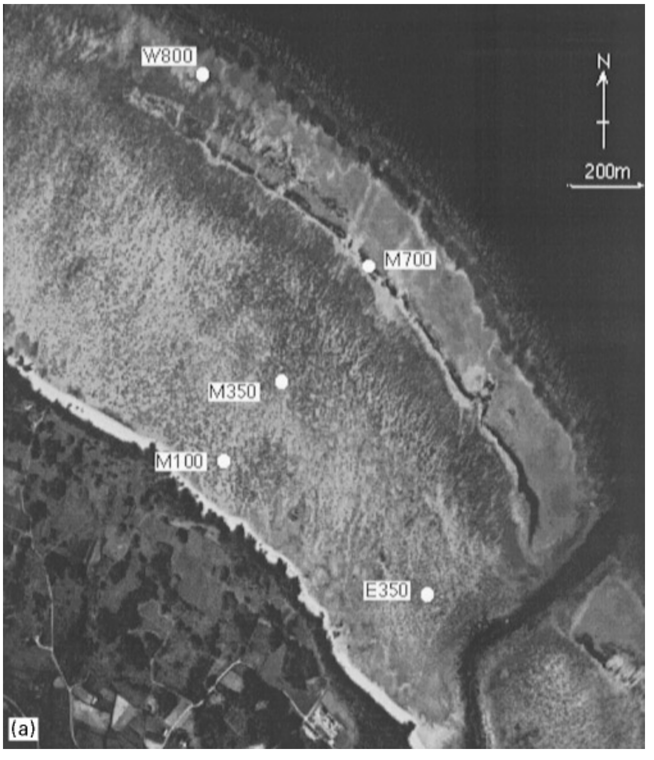


Fig. 1 Map of Ishigaki Island, and location of Kabira Reef. The wind rose depicts the annual distribution

Results

Figure 3 shows the current vectors at each observation point, wind vectors, and the calculated tide during the observation period. The current meters on W800 and M700 were exposed during low tides. In addition, they were overturned by surge currents. Therefore, there were some periods when the data collected at these observation points could not be used. These periods are labeled "No data" in Fig. 3.

The distribution of wind directions and velocities during the period from 12:00 on 11 March to 9:00 on 15 March can be divided into four short periods. There was almost no wind from 0:00 on 11 March to 0:00 on



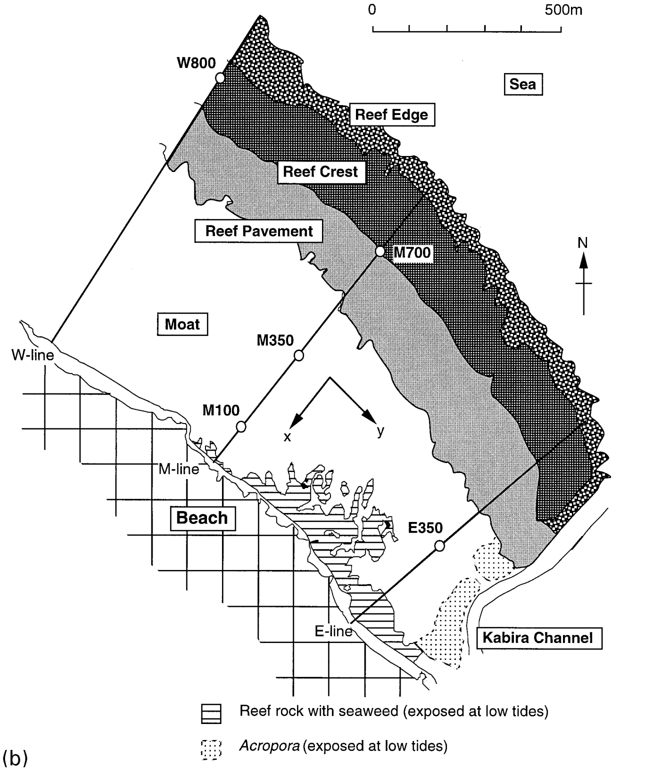


Fig. 2a Aerial photograph taken in 1994 and **b** geomorphological map of Kabira Reef. Circles show the observation points where we set current meters. Axis x represents the vector from ocean to shore

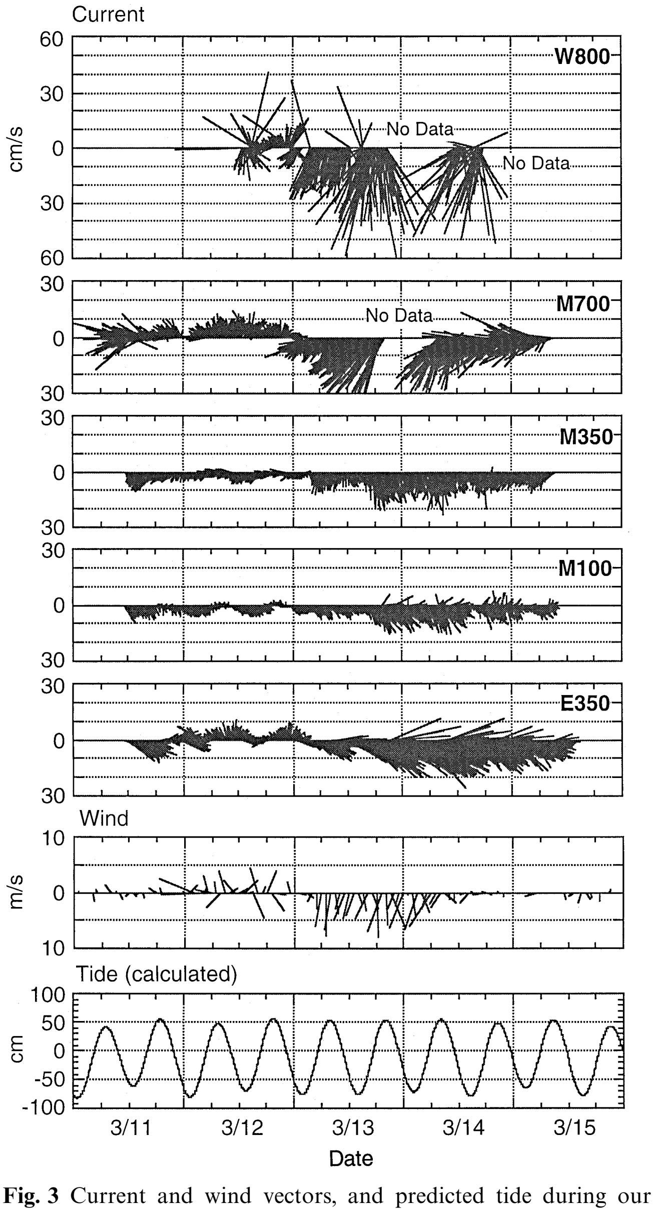


Fig. 3 Current and wind vectors, and predicted tide during our observation period

12 March. The southern wind was dominant from 0:00 on 12 March to 3:00 on 13 March, and its maximum value was 7 m/sec. The northern wind coming inshore occurred from 3:00 on 13 March to 12:00 on 14 March, and its maximum value was 8 m/sec. The northern wind was stronger than the southern wind Fig. 3. There was almost no wind again from 12:00 on 14 March to 9:00 on 15 March.

The predicted tide was semi-diurnal and showed almost the same pattern each day during our observation period. The tidal range was about 130 cm.

Water circulation under various wind conditions

In this study, we observed the water circulation under three wind conditions: no wind, southern wind, and northern wind. To study the circulation pattern, we calculated the mean velocity value every 15 minutes. Under each wind condition, we describe the circulation patterns for each tide condition: high tide, ebb tide, low tide, and flood tide. Figure 4a–d shows the current vectors under each wind condition.

(a). No wind I (Fig. 4a, from 12:00 on 11 March to 0:00 on 12 March). Ocean waters came into the moat over the reef crest and went out through Kabira Channel. During low tide, the reef crest was exposed and there was no inflow over the reef crest. However, circulation in the moat continued and water flowed out through Kabira Channel.

(b). Southern wind (Fig. 4b, from 0:00 on 12 March to 3:00 on 13 March). The pattern observed under the no wind condition described was weakened. The current velocity was generally lower, and the directions were changed according to the wind direction. This phenomenon is clearly seen at E350.

(c). Northern wind (Fig. 4c, from 3:00 on 13 March to 2:00 on 14 March). Under this condition, the pattern observed under no wind condition was strengthened.

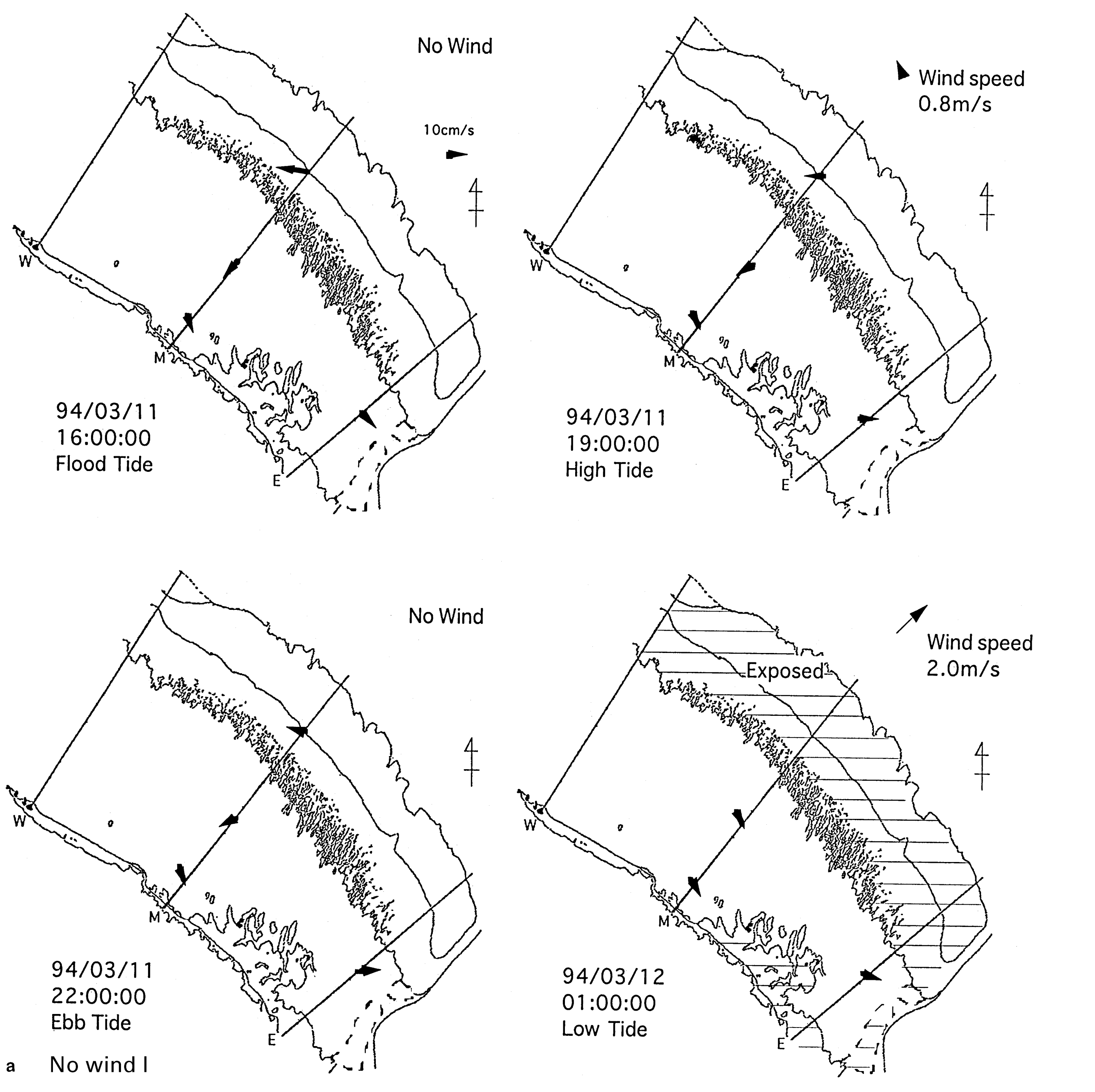


Fig. 4a–d Water circulation on Kabira Reef over 4 days (**a–d**) during flood, high, ebb, and low tide. **a and d** No wind conditions, **b** southern wind condition, and **c** northern wind condition were recorded

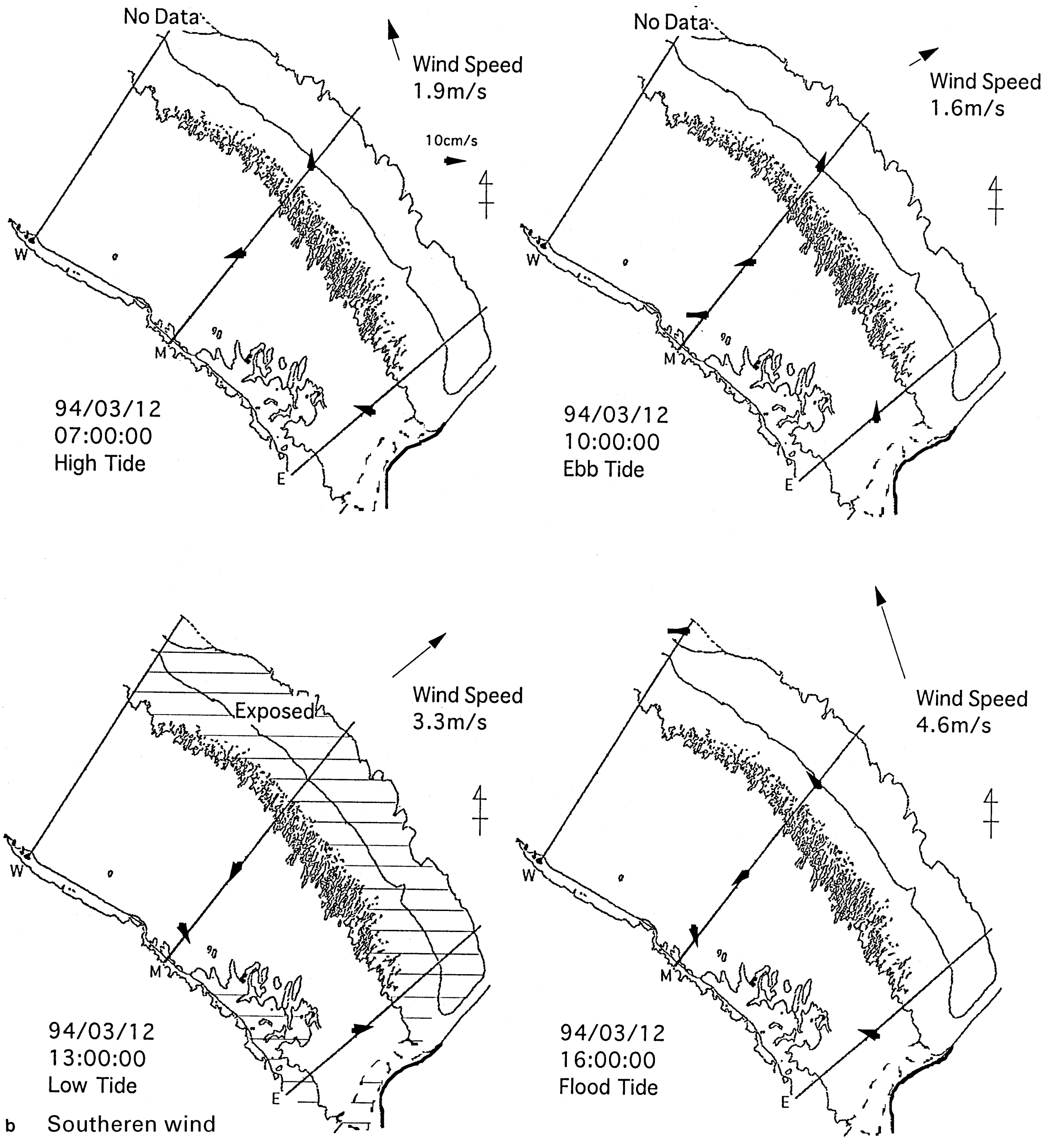


Fig. 4b.

The current velocity was generally higher. Ocean water inflow over the reef crest (W800 and M700) increased in comparison with the no wind condition.

(d). No wind II (Fig. 4d, from 12:00 on 14 March to 9:00 on 15 March). This figure also presents the circulation under a no wind condition, and the circulation is similar to the previous no wind condition. However, both inflow over the reef crest and the flow in the moat was greater.

Wind and water inflow on reef crest

We set x and y as the horizontal and vertical axes shown in Fig. 2. Thus the x-axis represents the vector from the ocean to the shore. Figure 5 shows the wind and current velocity over the reef crest (W800 and M700) along the x-axis. Positive values represent the current velocity from the ocean to the moat perpendicular to the reef crest. There was a small inflow over

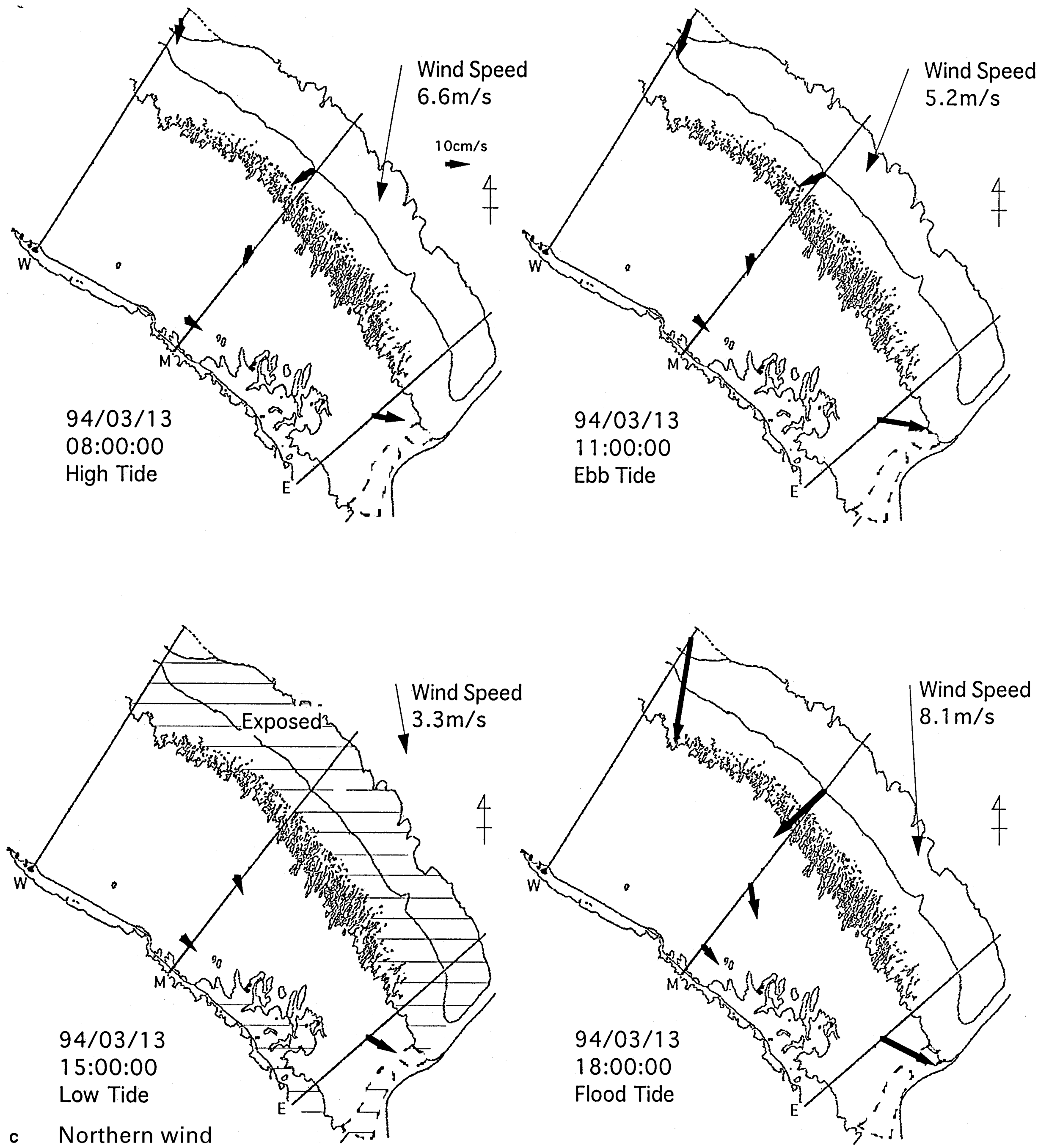


Fig. 4c.

the reef crest under the no wind condition I. Water flowed out from the moat under southern wind condition. Water inflow was amplified when the wind changed from the south to the north. Inflow continued after the wind stopped and the no wind condition returned. This pattern was similar for the two observation points (W800 and M700).

Discussion

Because northern and southern winds account for about 80% of the yearly wind condition (Fig. 1), our observation period is long enough to understand the water circulation on Kabira Reef. Water circulation

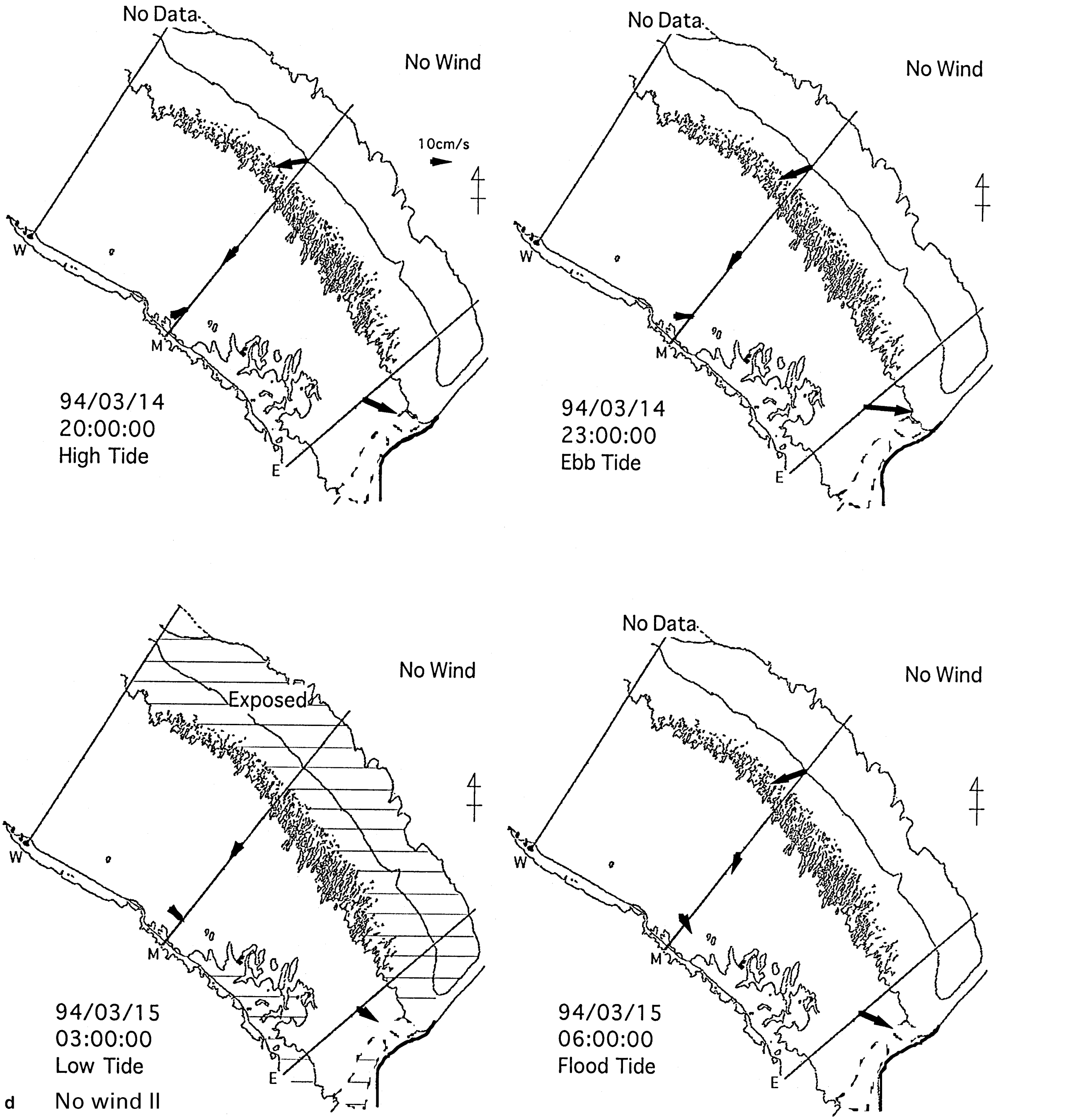


Fig. 4d.

changes significantly according to wind direction (Fig. 4a–d). The pattern under the no wind condition shows inflow from the reef crest and outflow through the channel. This pattern is in agreement with previous studies on fringing reefs (Tanimoto and Uda 1990; Wolanski *et al.* 1994). Some studies have reported a flow reversal at the beginning of the flood tide (Marsh *et al.*, 1981), however, on Kabira Reef, the circulation pattern under the no wind condition was almost the same irrespective of tide conditions (Fig. 4a). This basic circulation pattern is seen in Fig. 5, showing a steady inflow velocity over the reef crest during the no wind condition. We consider this constant circulation to be the fundamental pattern in this reef induced by ocean swells. Nakamura and Kudo (1996) showed that there were small swells off Kabira Reef with about 0.2 m significant wave height in calm periods in March 1995.

Because the tide range is almost constant (130 cm) during our observation period, we consider that the changes in the circulation in this reef (Fig. 4) must be due to the change of wind direction and induced change of ocean swells: the fundamental pattern is

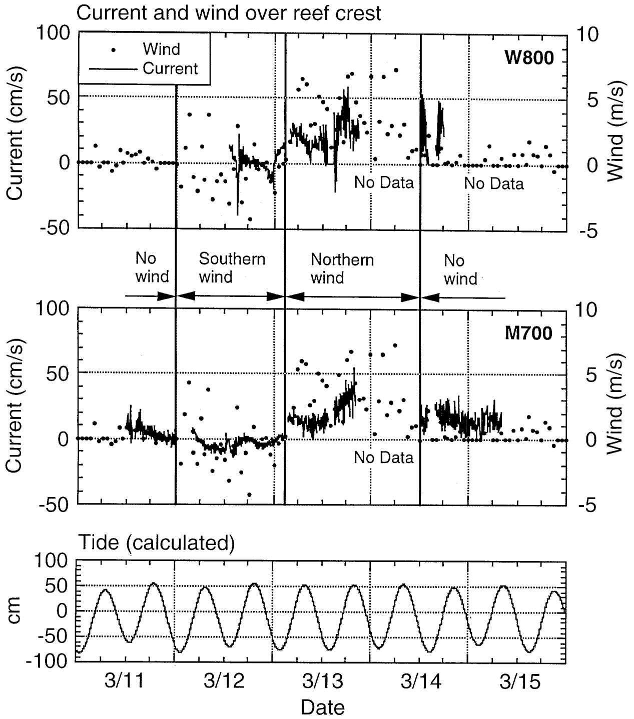


Fig. 5 Current and wind at W800 and M700 along the vector from the ocean to the shore, and tide during our observation period

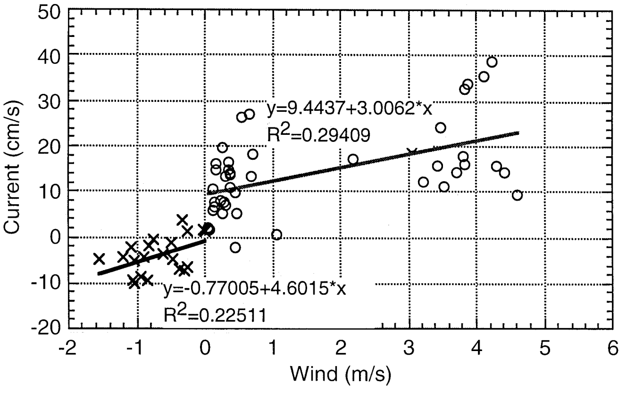


Fig. 6 Linear relationship between current and wind over the reef crest. Positive values are from the ocean to the shore (northern wind conditions, and negative values show southern wind conditions

weakened and strengthened under southern wind and northern wind conditions, respectively.

Figure 5 shows that the inflow of waters over the reef crest is influenced by wind direction. However, after 12:00 on 14 March when the northern wind stopped, the inflow was considerably greater than the values before 0:00 on 12 March corresponding to the no wind condition I. These conditions might cause the differences in the circulation patterns shown in Fig. 4d. Inflow over the reef crest was caused by wind-driven current and wave-overtopping resulting from the development of ocean swells. As the northern wind blew a wind-driven water inflow occured immediately. After that, ocean swells developed and broke on the reef crest. When the northern wind stopped, the swells persisted for a while and broke on the crest producing a water inflow. Thus, we believe that the inflow after 12:00 on 14 March was caused by wave-overtopping.

Next we explain the circulation in the moat quantitatively by the fundamental constant pattern, the wind, and inflow over the reef crest. Swells develop by winds, therefore, in order to model the inflow over the reef crest, we used a linear function between wind and the inflow velocity as proposed by Pickard (1986) because we have no data on swells and induced wave-overtopping to explain the current over ther reef crest. Figure 6 shows the correlation between wind and current velocity on the reef crest at M700 under both southern and northern wind conditions. Wind values are averaged over 7 h to remove the effect of the development of ocean swell. Current velocity over the reef crest (Ur) is described by the following equations. Under southern wind conditions:

$$Ur = -0.77005 + 4.6015 \cdot Wx \tag{1}$$

and under northern wind conditions:

$$Ur = 9.4437 + 3.0062 \cdot Wx \tag{2}$$

The volume transport at each observation point in the moat (Qx and Qy) is expressed by the following equations:

$$Qx = H \cdot (Cw \cdot Wx + Cxy \cdot Wy) + H \cdot Qcx + Cx \cdot d \cdot Ur \tag{3}$$

$$Qy = H \cdot (Cw \cdot Wy + Cyx \cdot Wx) + H \cdot Qcy + Cy \cdot d \cdot Ur \tag{4}$$

where Wx and Wy are x and y components of the wind vectors, H is the depth at the observation points, and d is the depth on the reef crest. These values are taken from observations. Ur is the current velocity over the reef crest. Ur values are obtained from Eqs. (1) and (2). Cw is the direct effect of wind on current velocity. Cxy (Cyx) are the effects of the $x(y)$ component of the wind on the y (x) component of current, considering the effect of the topography. Qcx and Qcy are constants corresponding to the fundamental circulation pattern as discussed already. Cx and Cy are coefficients expressing the effects of inflow over the reef crest. Thus, each term represents the volume transport induced by the wind (first term), fundamental circulation (second term), and inflow over the reef crest (third term).

We used the least square method to determine the values of variables in Eqs. (3) and (4) (Cw, Cxy, Cyx, Qcx, Qcy, Cx, and Cy) which give the best fits between the calculated and observed values of volume transport at M350, M100, and E350.

Figure 7a–c shows the observed and calculated volume transport values at each observation point.

Table 1 shows the calculated values of variables (Cw, Cxy, Cyx, Qcx, Qcy, Cx, and Cy) and the regression coefficients (R^2) between observed and calculated values of volume transport on the x and y axis at each observation point. Calculated values and observed values fit well and correlation coefficients (r-squared) range from about 0.43 to 0.63 except for M100 (correlation coefficient is 0.05). Fundamental circulation values (Qcx and Qcy) are in agreement with the observed values described in Fig. 4a. The effect of inflow over the reef crest (Cx and Cy) is greatest at E350, located at the exit of the moat where the water exiting the moat concentrates. These results show the validity of our regression. As for M100, there are differences between the observed and calculated values probably because the volume transport values are small.

As the inflow over the reef crest depends on wind, we attribute the water volume transport in the moat to two factors: wind and a fundamental circulation pattern. Figure 8 shows the ratio of the wind-driven component (the sum of calculated volume transports induced directly by wind and by inflow over the reef crest) to the fundamental component induced by swells in calm periods. Generally the wind-driven component is greater than the fundamental component, and the ratio ranges between 3 and 10 at M350 and 2 and 7 at E350 (in absolute values, during high tide) under the southern and northern wind conditions, respectively. Therefore, wind is the main factor causing the differences in circulation in Kabira Reef.

Our approach is very simple and practical for modelling backreef water circulation and can be applied to other reef systems of similar geometry. In order to account for the flow reversal at the beginning of flood tide described by Marsh et al. (1981), we could modify Qcx and Qcy to depend on tide. Furthermore, Tanimoto and Uda (1990) reported the effect of wind direction on the trajectories of drifting buoys and concluded that the effect of the wind is small. This situation could be due to Qcx or Qcy being greater than the wind-driven component. However, what we consider important here is to observe the change of the

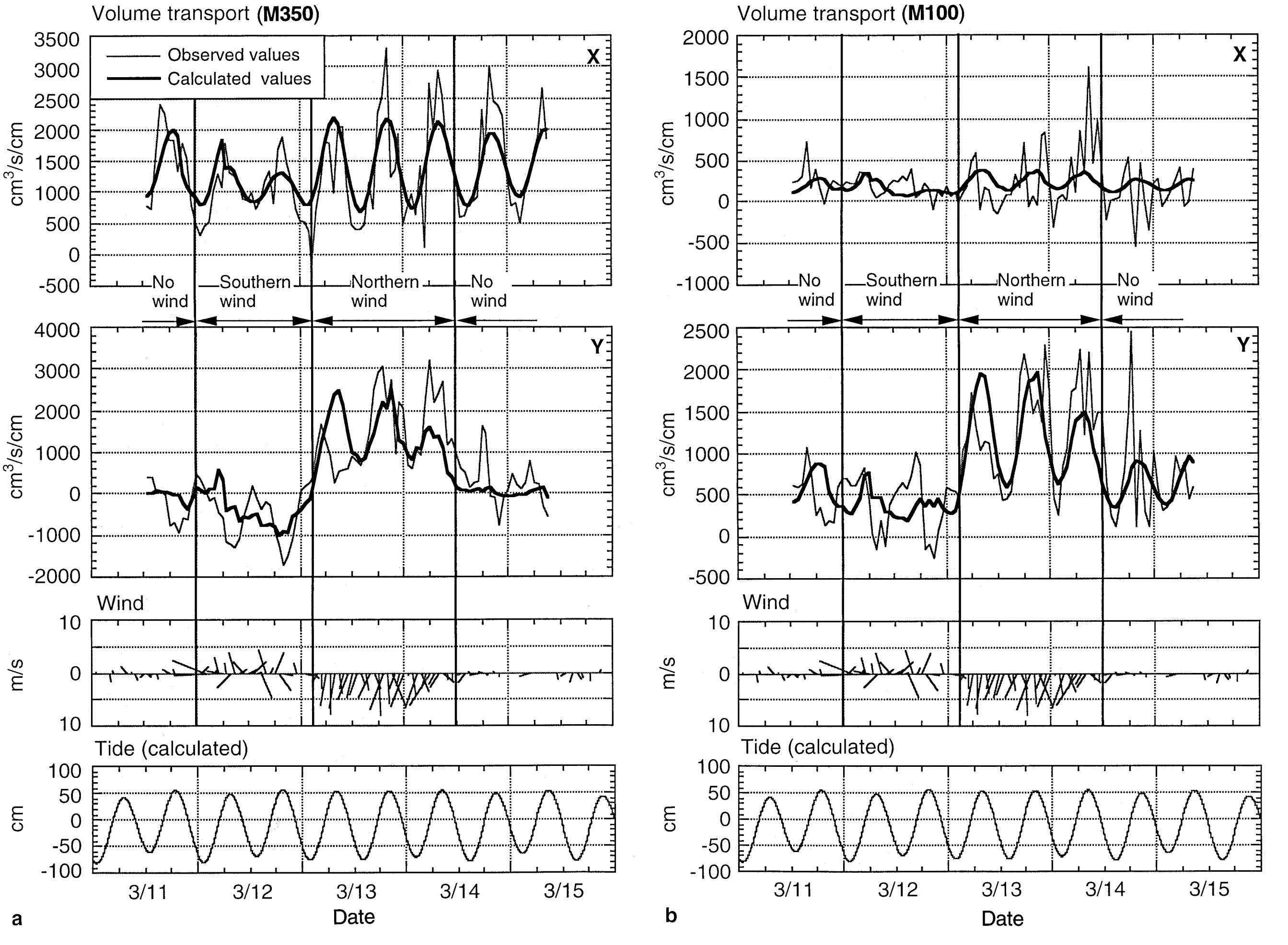


Fig. 7a–c Observed and calculated volume transport. The upper two figures show the observed and the total calculated volume transport on the x-axis and the y-axis. Narrow and bold lines represent the observed and calculated values, respectively. The middle figure shows wind vectors. Lower figure shows the predicted tide during our observation period

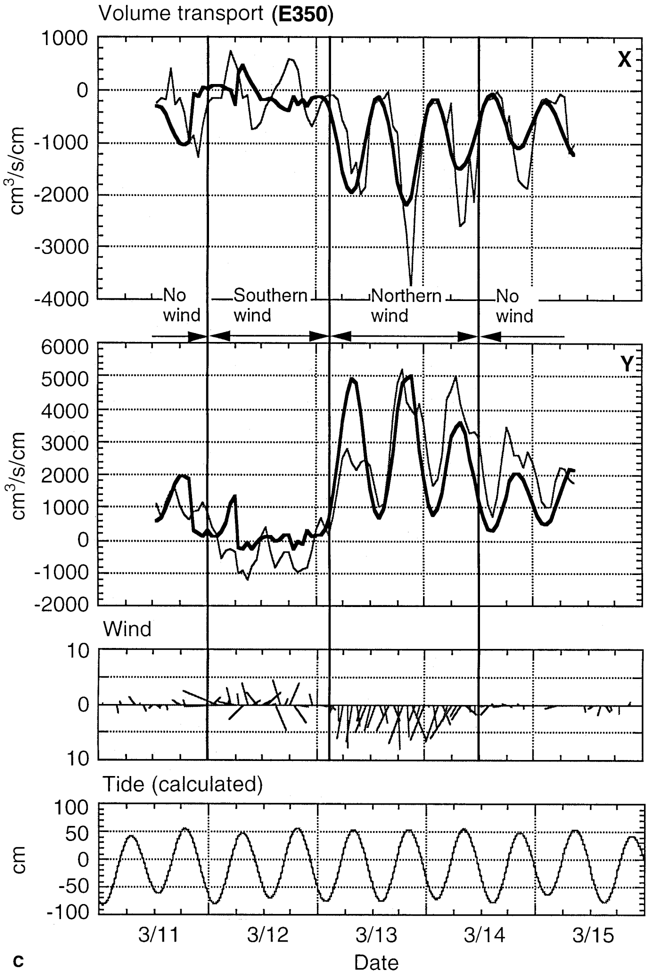


Fig. 7 (continued)

Table 1 The coefficients of each component at M350, M100, and E350

	M350	M100	E350
Cw	– 0.00313	0.00199	0.01615
Cxy	– 0.00103	– 0.02124	– 0.019028
Cyx	0.02094	0.00635	0.00170
Qcx	5.50400	0.93504	– 1.46934
Qcy	– 1.01818	2.84457	3.23751
Cx	0.36412	0.03055	– 0.66605
Cy	0.14175	0.17329	1.09074
R^2	0.61, 0.59	0.05, 0.43	0.51, 0.63

Cw: direct effect of wind on current velocity
Cxy (*Cyx*): effects of the *x* (*y*) component of the wind on the *y* (*x*) component of current
Qcx and *Qcy*: constants corresponding to the fundamental circulation
Cx and *Cy*: coefficients of the effects of inflow over the reef crest
R^2: correlation coefficients between observed and calculated values of volume transport (left: x-axis, right: y-axis)

circulation pattern according to changing wind conditions and thereby estimate the contribution of the wind. Prager (1991) considered that ocean swell and the induced inflow over the reef crest are constant probably because her study site is situated in a trade wind area. Our results show that inflow over the reef crest at Kabira Reef is dependent on the wind. Monsoonal winds result in a circulation pattern classifiable by wind conditions, while trade winds result in a more stable circulation pattern.

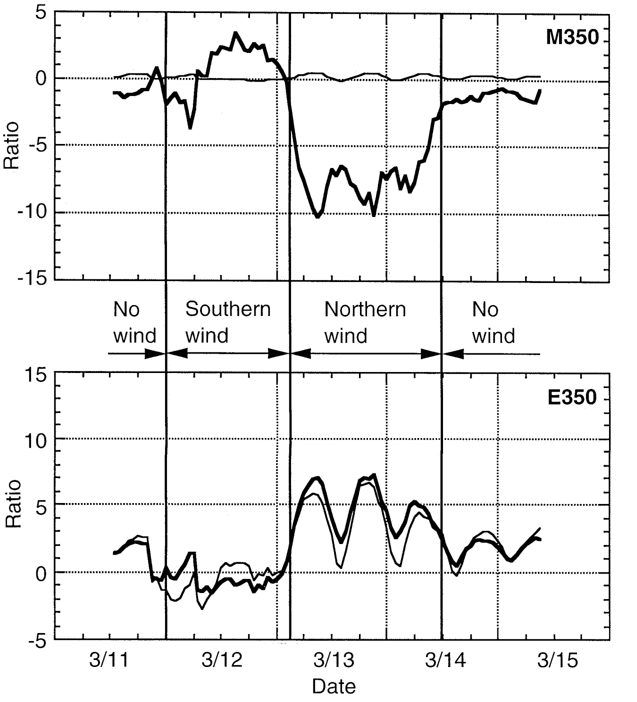


Fig. 8 The ratio of the component of the wind to fundamental volume transport at M350 (*above*) and E350 (*below*). Narrow and bold lines represent the ratios on the x-axis and the y-axis, respectively

Furthermore, our study is the first to estimate the contribution of the wind to the volume transport in a coral reef moat. Wind has a strong influence on the circulation in Kabira Reef. We explain this circulation by dividing it into a wind-driven component and a fundamental circulation component, and we can apply these results to monsoonal circulation. In Ishigaki Island, the dominant wind is from the south in summer and from the north in winter. Therefore, the circulation pattern in summer is expected to show the pattern described here for the southern wind condition, and the pattern in winter is expected to show the northern wind condition pattern. The pattern under the northern wind condition should be dominant throughout the year on Kabira Reef because the northern winds do dominate throughout the year (Fig. 1). This idea is supported by the arrangement of coral patches (Fig. 2a) which correspond to the pattern under the northern wind condition.

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References

Andrews JC, Pickard GL (1990) The physical oceanography of coral-reef systems. In: Dubinsky Z (ed) Ecosystems of the World Vol. 25 Elsevier Amsterdam, pp 11–48

Atkinson M, Smith SV, Stroup ED (1981) Circulation in Enewetak Atoll lagoon. Limnol Oceanogr 26–6 : 1074–1083

Frith CA (1981) Circulation in a platform reef lagoon, One Tree Reef, southern Great Barrier Reef. Proc 4th Int Coral Reef Symp 1 : 347–354

Frith CA, Mason LB (1986) Modelling wind driven circulation One Tree Reef, Southern Great Barrier Reef. Coral Reefs 4 : 201–211

Marsh JAJ, Ross RM, Zolan WJ (1981) Water circulation on two Guam reef flats. Proc 4th Int Coral Reef Symp 1: 355–360

Nakamori T, Suzuki A, Iryu Y (1992) Water circulation and carbon flux on Shiraho coral reef of the Ryukyu Islands, Japan. Cont Shelf Res 12–7/8 : 951–970

Nakamura H, Kudo K (1996) Modeling of the flow induced by reef crest on the water circulation around Kabira Reef. JAMSTECR 33 : 55–64 (in Japanese)

Parnell KE (1988) The hydrodynamics of fringing reef bays in the Great Barrier Reef Marine Park. Proc 6th Int Coral Reef Symp 2 : 503–508

Pickard GL (1986) Effects of wind and tide on upper-layer currents at Davies Reef, Great Barrier Reef, during MECOR (July-August 1984). Aust J Mar Freshwater Res 37 : 545–65

Prager EJ (1991) Numerical simulation of circulation in a Caribbean-type backreef lagoon: a preliminary study. Coral Reefs 10 : 177–182

Roberts HH, Murray SP, Suhaida JN (1975) Physical processes in a fringing reef system. J Mar Res 33–2 : 233–260

Roberts HH, Wilson PA, Lugo-Fernandez A (1992) Biologic and geologic responses to physical processes: examples from modern reef systems of the Caribbean-Atlantic region. Cont Shelf Res 12–7/8 : 809–834

Tanimoto T, Uda T (1990) Study on waves, nearshore current and beach changes on coral reef. Report of PWRI 181–3 : 85–182 (in Japanese)

Wolanski E, Delesalle B, Dufour V, Aubanel A (1994) Modeling the fate of pollutants in the Tiahura Lagoon, Moorea, French Polynesia. 11th Australasian Conf Coastal and Ocean Engineering

Yamano H (1996) The zonation of Kabira Reef, Ishigaki Island, Southwest Japan. Thesis, Department of Geography, University of Tokyo: 72p (in Japanese)